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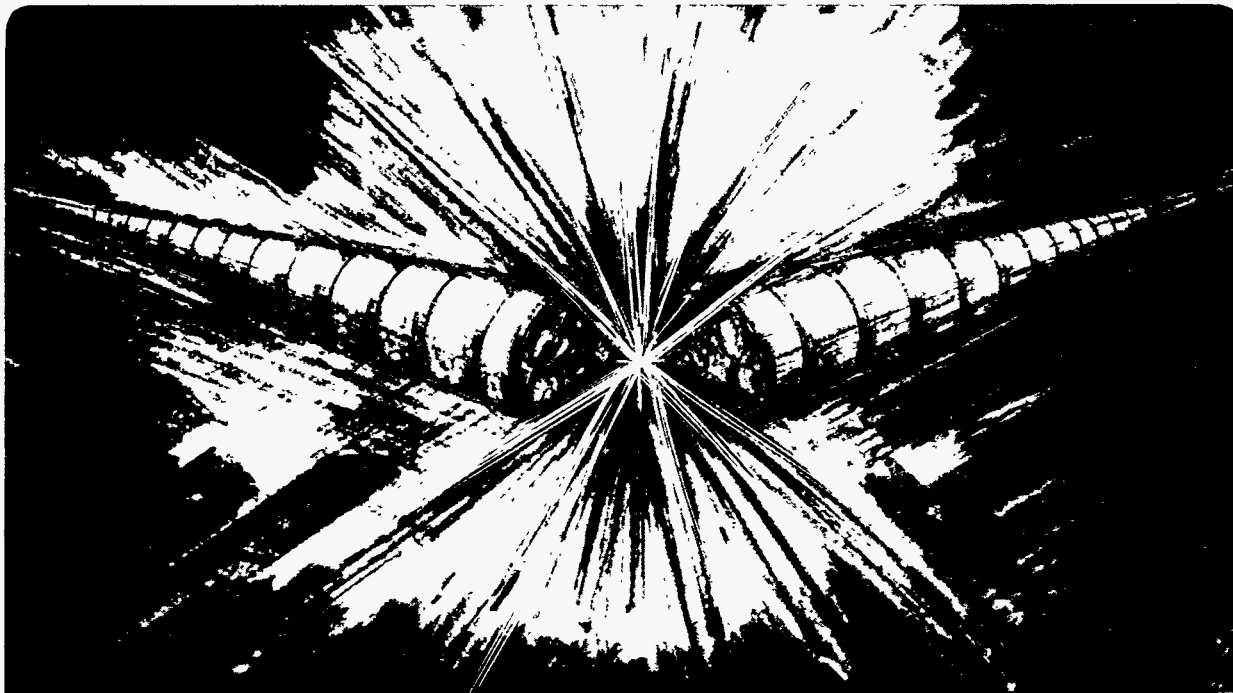
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Design Parameters for a 7.2 Tesla Bending Magnet for a 1.5 GeV Compact Light Source*

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Abstract---This report describes the design for a 7.2 tesla superconducting dipole magnet for a compact synchrotron light source. The proposed magnet is a Vobly type modified picture frame dipole that has the flux returned through unsaturated iron. In this magnet, The iron in the pole pieces is highly saturated. Separately powered coils around the pole pieces are used to direct the flux lines until the flux can be returned through the unsaturated iron. The proposed dipole will develop a uniform field over a region that is 80 mm high by 130 mm wide over a range of central induction from 0.4 T to almost 8 T. Each dipole for the compact light source will have a magnetic length of about 0.38 meters.

I. BACKGROUND ON THE STORAGE RING

The magnet that is described in the report is designed for use in a compact electron storage ring that is to produce intense x rays with energies up to 35 keV[1,2]. Storage ring energies up to 1.5 GeV are proposed. In order to produce synchrotron radiation x ray beams with a critical energy greater than 10 keV, the central induction of the dipoles used to produce the synchrotron radiation must be greater than 6.8 tesla [3]. The machine is designed primarily as a light source for industrial, biological and medical applications. As a result, the ring must be compact and the ring must be relatively inexpensive to build.

The ring has a hybrid magnet structure, consisting of superconducting dipoles and room temperature quadrupoles and sextupoles. The shape of the ring is racetrack. The two arcs are identical and each arc is symmetric about its center. The two straight sections joining the arcs have the same length but each has different structure.

Each of the two arcs has three bending stations where the electron beam is bent 60 degrees. Each bending station contains two straight cold iron dipoles that bend the beam and produce the synchrotron radiation x rays. The x rays that are delivered to the user come from the downstream cold iron dipole. The bending induction required for a 1.5 GeV ring that produces x rays with a critical energy of 10.4 keV is 6.894 T. In addition to providing the bending needed in the ring, the straight dipoles also provide defocusing (through edge focusing) to the lattice. Two bending stations and the arc focusing between the stations are shown in Fig. 1. The pair of straight cold iron dipoles are shown within the cryostat vacuum vessel boundary.

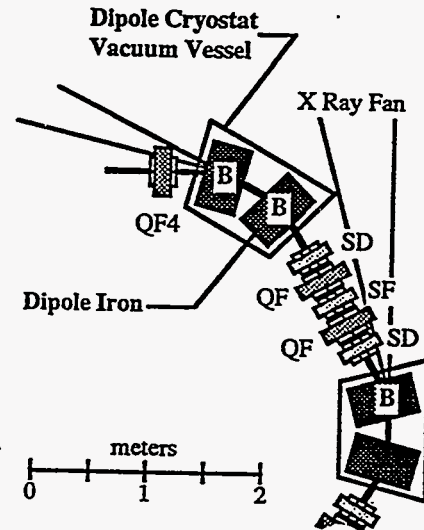


Fig. 1 A section of a 1.5 GeV Light source Synchrotron Showing Two Bending Stations

II. THE DIPOLE DESIGN REQUIREMENTS

The key to making a compact electron storage ring is the fabrication of short high field dipoles that have the end field characteristics of room temperature, low field copper and iron dipoles. Within the magnet, the field quality has to be very good. Beam dynamics studies suggest that the integrated field has to be good to one part in 10000 over a region that is ± 20 mm wide around the electron beam. Picture frame magnets can have a very good field over the entire width of the magnet pole. Fig. 2 shows the gap region for the dipoles shown in Fig. 1. The magnet horizontal aperture (pole width) is governed by beam sagitta, the x ray fan allowance, the 15 sigma beam width, the width of the x ray absorber and the insulation thickness between the warm bore tube and the 4.4 K region. The magnet vertical aperture (the cold gap) is governed by the 15 sigma beam height and the insulation thickness between the warm bore tube and the pole.

The x ray absorber in the downstream dipole vacuum chamber absorbs the synchrotron radiation energy generated in the upstream dipole (See Fig. 1). The vacuum chamber for the dipole pair can be cooled to 180 K using a conventional refrigerator provided the beam current in the storage ring is not too high (less than 30 mA). A 180 K vacuum chamber helps maintain the good vacuum required for the beam. If a high beam current light source is desired, the machine lattice has to be changed to split the dipoles in the pair[3].

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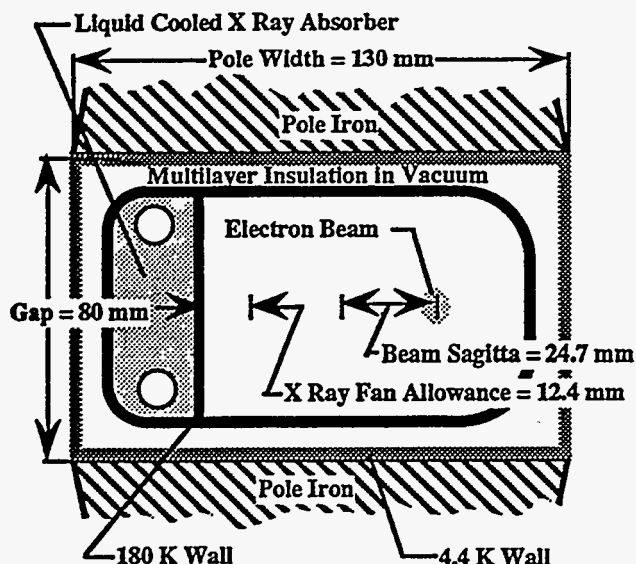


Fig. 2 The Gap Region of the Compact Ring Dipole
- Shown in the Storage Ring Section in Fig. 1

III THE 7.2 TESLA SUPERCONDUCTING DIPOLE

The design for the dipole is based on an idea proposed by Pavel Vobly at INP Novosibirsk.[4,5] Fig. 3 shows a cross-section through the center of a 7.2 tesla Vobly dipole. The dipole shown in Fig. 3 consists of three different coils: 1) The gap coils generate the magnetic flux within the gap. The current in the gap coil is approximately linear with the magnetic induction within the gap. 2) The crossover coils in effect carry the current from one side of the gap to the other side of the gap. This coil is in series with the gap coil; it acts as the end crossover coils act in a conventional H magnet

with unsaturated iron poles. Away from the gap, the gap and crossover coil currents cancel each other. 3) The function of the shield coil is to keep flux from leaking out of the pole as it becomes saturated. When the current in the shield coil is correctly selected, the flux lines from gap stay perpendicular to the pole face even within the pole iron. The shield coil current will be nearly zero when the induction in the gap is less than 2 T. As the gap induction increases above 2 T, the current in the shield coil increases linearly with the gap induction minus the saturation induction of the iron ($\sim 2T$).

The dipole shown in Fig. 3 will generate a uniform field over a range of induction from 0.4 to 7.8 T, provided that the current density in the shield coil is correctly chosen with respect to the current density in the gap and crossover coils. The shield coil current can be set so that sextupole, decapole and 14 pole field components are nearly zero. The excitation function for the shield coil can be modified by changing the height and slope angle of the shield coil [6]. The induction in the pole iron and the gap will be the same while the rest of the iron will be unsaturated. The iron cross-section in Fig. 3 can be optimized (for example, cutting off the corners) to reduce the dipole cold mass.

Fig. 4 is a three dimensional view of the dipole coil system. The arrows in Fig. 4 show the direction of current flow. Fig. 5 is a cross-section of the 7.2 tesla magnet in the plane of the electron beam. The direction of current flow in the three types of coils is also shown in Fig. 5. The location of the two magnets in the pair with respect to each other is also shown. From Figs. 3, 4 and 5, one can see that the windings in the dipole can be quite simple. The gap and crossover coils can be wound as flat pancakes with no bends out of the plane of the pancake. The coil corner radii should be kept as small as possible. The support of the coils against magnetic forces is very important at high fields.

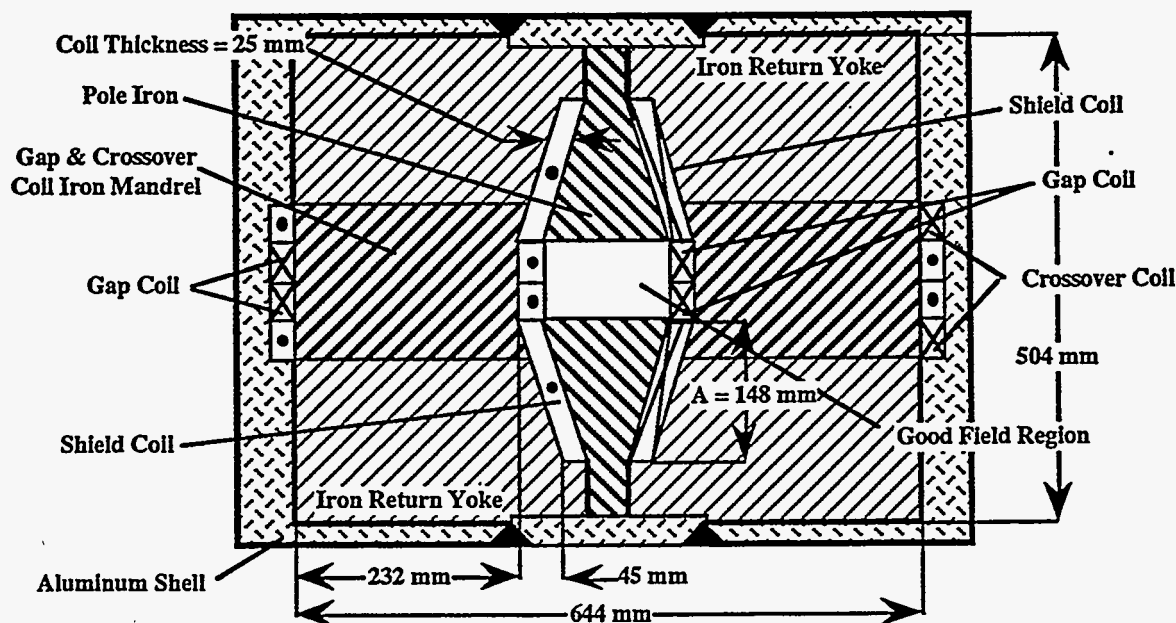


Fig. 3 A Cross-section of a 7.2 T Dipole Perpendicular to the z Axis (the beam direction)

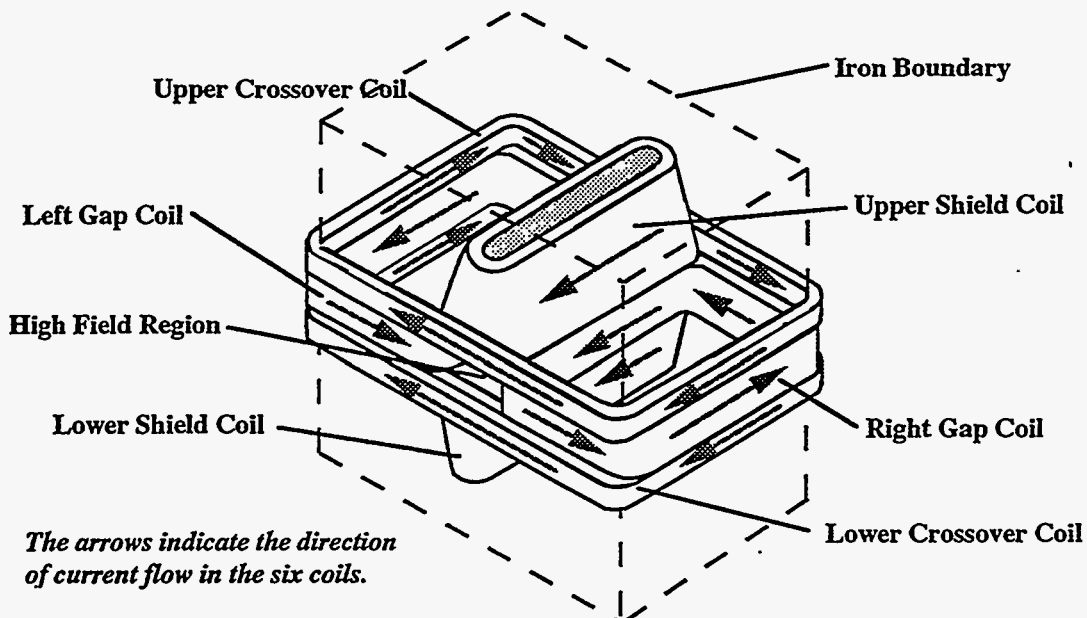


Fig. 4 A Three Dimensional Artists Conception of the 7.2 Tesla Dipole Coil System

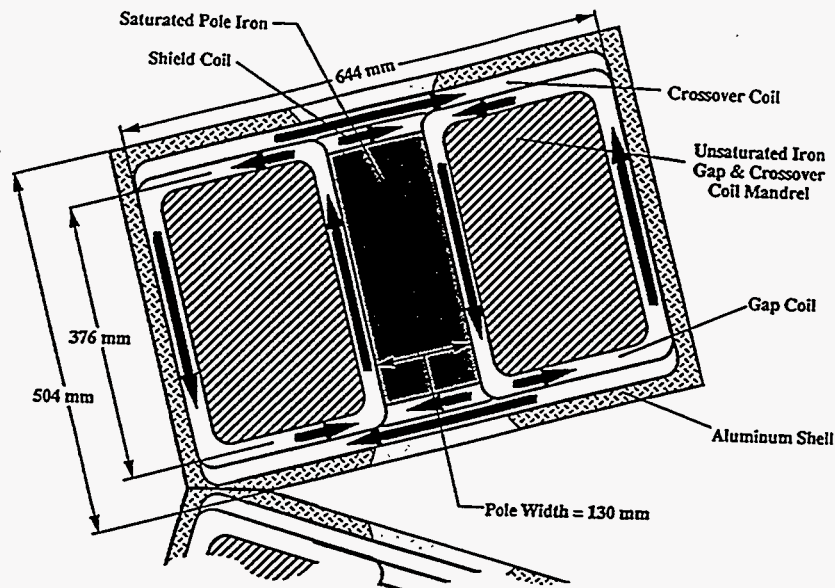


Fig. 5 A Cross-section through the Center of the 7.2 T Dipole Perpendicular to the Y Axis in the Plane of the Electron Beam (It should be noted that the beam vacuum chamber is not shown in this figure in order to show the current paths.)

The flux plot in Fig. 6 illustrates how the shield coil contains the magnetic flux in the iron pole pieces when the central induction is 7.0 tesla. Fig. 6 shows that the flux density in the pole is the same as the flux density within the gap. The current density in the shield coil is 166.6 MA per square meter while the current density in the gap and crossover coils is 270.0 MA per square meter. (See Fig. 7) The high field point in the two dimensional coil cross-section is nearly the same as the central induction of the dipole. The high field point is found outside the iron at the juncture of the gap and crossover coils.

Table I presents the basic magnet parameters for the 7.2 tesla dipole shown in Figs. 3, 4, and 5. While the design

central induction for the magnet is 7.2 tesla, its nominal operating central induction in the 1.5 GeV ring configuration shown in Fig. 1 is closer 6.9 tesla. The required integrated dipole for the ring is about 2.62 tesla meters per 30 degree bend segment

If one bases the coil design shown in Fig. 3 on a cable made from SSC inner conductor (with a copper to S/C ratio of 1.4), the dipole will operate at about 91% of its critical current along the load line (based on a metal packing fraction of 0.7 and an operating temperature of 4.4 K) when the central induction is 7.2 T. It appears that the SSC inner superconductor can be cabled into conductor of almost any desired current for this application.

Table I COMPACT LIGHT SOURCE
DIPOLE PARAMETERS

Dipole Bend Angle (degrees)	30.0
X Ray Fan Angle (degrees)	20.0
Design Induction at Center(T)	7.2
Magnetic Length (mm)	~380
Magnet Cold Gap (mm)	80.0
Magnet Iron Pole Width (mm)	130.0
Shield Coil Height (mm)	148.0
Coil Thickness (mm)	25.0
Stored Energy at Design Induction (kJ)	~230
Peak Induction in Winding (T)	~7.3
Iron Length (mm)	376.0
Iron Width (mm)	644.0
Iron Height (mm)	504.0
Estimated Cold Mass per Dipole (kg)	~1100.

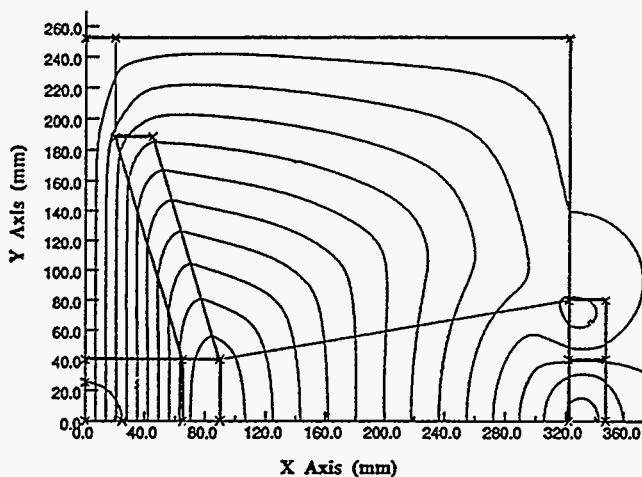


Fig. 6 A Two Dimensional Flux Plot for the Dipole
at a Central Induction of 7 tesla

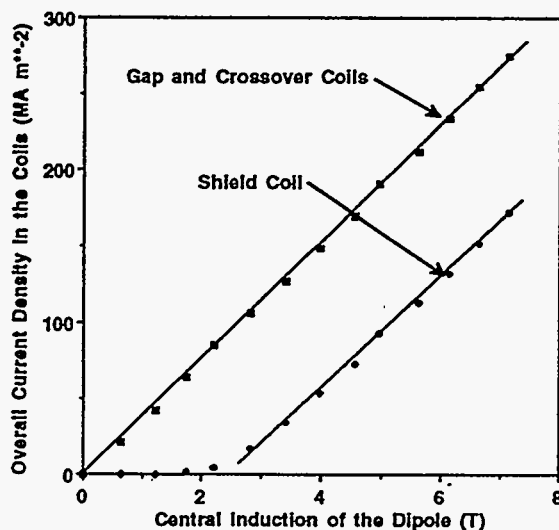


Fig. 7 Current Density in the Gap and Crossover Coils and
the Shield Coils as a Function of Central Induction

IV. CONCLUSION

A compact synchrotron with 7.2 tesla superconducting bending magnets appears to be feasible. The key to making the compact synchrotron is having a short high field bending magnet that has end field characteristics that are similar to conventional low field copper iron magnets. This means that the magnetic flux must be constrained in the poles while the magnet is running at high field. The picture frame magnet design proposed by Pavel Vobly of INP Novosibirsk has this desirable characteristic even for short dipoles. The primary disadvantage of the Vobly magnet design is that it requires two separate power supplies in order for the magnet to produce good field quality over a range of inductions.

The cost of the dipole is primarily a function of the width of the pole, not the gap. Since most of the iron in the magnet is unsaturated, the iron height and width is a function of the pole width and the saturation induction of the iron. The dipole design presented in this report is not very efficient in its use of superconductor. Unlike many superconducting dipoles, the cost of the superconductor is not a large part of the capital cost of this magnet. However, it would be difficult to justify the use of the Vobly design for the long dipoles that are typically used for high energy physics machines.

V. ACKNOWLEDGMENTS

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